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The Department of Defense lacks refined capability to assess and predict potential impact of tactical and experimental sound sources in the presence of marine mammals. Although there is sustained concern over the effects on marine mammals of man made sound in the oceans, there is very little direct information about what sound frequency-intensity combinations damage marine mammal hearing. Our broad objective is to transition information about effects of DoD sound types on marine mammal auditory anatomy and acoustic ecology to predictive models and mitigation tools. This effort responds directly to the DoD capability to comply with the National Environmental Policy Act requirements and will contribute directly to answering the National Council's Research Needs related to the effect of low-ferquency sound on marine mammals (1994, 2000). This final report summarizes the accomplishments of SERDP Project CS-1082 spanning the lifetime of the project from FY98-FY-00.

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Final Report for SERDP Project CS-1082

Information and Technology Tools for Assessment and Prediction
of the Potential Effects of Military Noise on the Marine Environment

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Introduction.

The Department of Defense lacks refined capability to assess and predict potential impact of tactical and experimental sound sources in the presence of marine mammals. Although there is sustained concern over the effects on marine mammals of man made sound in the oceans, there is only very little direct information about what sound frequency-intensity combinations damage marine mammal hearing. Our broad objective is to transition information about effects of DoD sound types on marine mammal auditory anatomy and acoustic ecology to predictive models and mitigation tools. This effort responds directly to the DoD capability to comply with the National Environmental Policy Act requirements and will contribute directly to answering the National Research Council's Research Needs related to the effect of low-frequency sound on marine mammals (1994, 2000). This final report summarizes the accomplishments of SERDP Project CS-1082 spanning the lifetime of the project from FY98-FY00.

Task 1. Comparative Cetacean Auditory Anatomy

Accomplishments.

Task 1 was a study comparing the evidence for normal versus pathological changes of marine mammal ear anatomy. Prior to FY98, there were no specific effort directed at understanding whether marine mammals, like humans and other land mammals, have

progressive, age-related hearing changes or disease that can potentially skew our understanding of noise effects on these animals. Our objective was to provide evidence of the relative occurrence of presbycusis (age-related hearing loss), sociocusis (sociogender-related hearing loss), and pathology (e.g., disease-related hearing loss).

The pool of samples consisted of twenty ears from eleven bottlenose dolphins (*Tursiops* spp.) sourced from the U.S. Navy and provided to Dr. Darlene Ketten (Woods Hole Oceanographic Institution; WHOI) for analysis. By the end of FY99, Magnetic Resonance (MR) scans had been made for five of nine ears, and CT scans had been completed for 20 of 20 ears. Histology was completed for seven ears, with 13 in various stages of preparation. To increase the pace of analysis, the histology process was modified and enhanced where possible. One ear may have been of sufficient quality to warrant Electron Microscopy in mid-FY00 but no report is available.
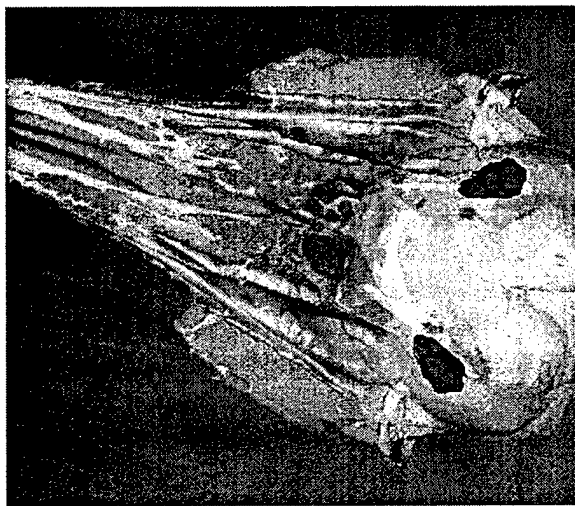
Integrated data from CT and MRI scans are depicted in this colorized 3D rendering. Here, we are looking from the bottom of the skull, with the rostrum to the left. The skull appears as gray. The bullae in which the middle and inner ear structures reside are colored red. Fatty tissues that are related to sound conduction are colored tan.

Figure 1. 3D Reconstruction of Auditory Anatomy in a Dolphin Head.

An exciting technical step was taken in Ketten's laboratory in FY99. Data from CT and MRI scans were integrated, depicted in the colorized 3D rendering in Figure 1. The dolphin head is viewed from the bottom of the skull, with the rostrum to the left. The skull appears as gray. The bullae in which the middle and inner ear structures reside are colored red. Fatty tissues that are related to sound conduction are colored tan. This image is a snapshot taken from a fully 3D process, which allows the user to visualize anatomical structures in a rotatable image. The figure clearly illustrates a unique quality of cetaceans – their ear bones (bullae; in red) are external to the skull, in contrast to all other mammals for which the middle and inner ear structures are internal to the skull. In FY00, a pilot study was scheduled to explore inclusion of sensorineural data taken from histology, but no report is available.

Task 1 Technology Transfer. None.
Task 1 Publications. None.
Lessons Learned.

Although the timeframe and funding for preparation, measurement, and analysis of all 20 Tursiops ear samples that had been scheduled for this study was planned in collaboration with WHOI, they did not deliver the scheduled analyses and reports. The lack of publications and conference presentations strongly compromises the planned Technology Transfer for Task 1 and the outward signs of success by SERDP. In the end, however, technology transfer has occurred in one fashion – the technical skills and capabilities of the WHOI lab developed during this project are being applied to WHOI's participation in the Office of Naval Research "Effects of Sound on the Marine Environment" program.

Task 2. WhalEar Computational Model of Baleen Whale Hearing

Accomplishments: Anatomical Analyses

The objective of Task 2 was to construct state-of-the-art computational models of baleen whale hearing and auditory processes, named *WhalEar* models. These models were founded upon comparative mammalian sensory processes and incorporated information about marine mammal psychophysics and neuroanatomy. Figures of merit for the models were based on psychophysical and evolutionary biological principles. Successful models were applied to understanding auditory processes implicated in potential impacts of anthropogenic sound on baleen whales.

As was true in Task 1, anatomical analyses were contracted to Dr. Darlene Ketten (WHOI). The pool of baleen whale ear samples consisted of six humpback whale ears, two fin whale ears, one blue whale ear, and three gray whale ears. By the end of FY99, MR scans were completed for two of two ears, and CT scans had been completed for all eleven ears. Histology was completed for two humpback ears, and was in progress for the remaining samples. No further information has been made available by WHOI. As of FY99, a technique for creating 3D reconstructions from histology slices had been demonstrated for one humpback ear, presented in Figure 2.

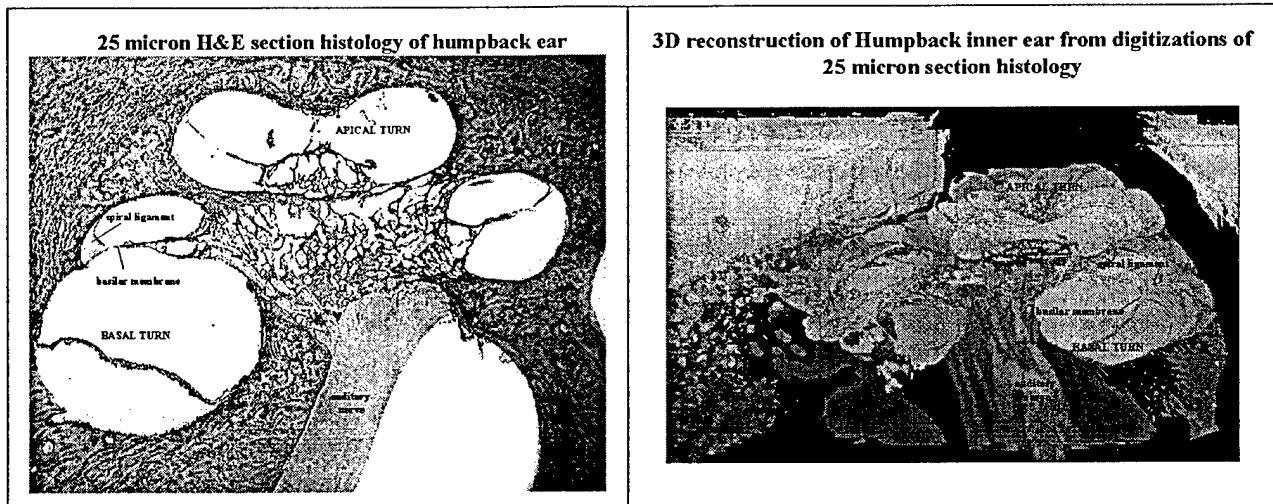| 25 micron H&E section histology of humpback ear	3D reconstruction of Humpback inner ear from digitizations of 25 micron section histology

Figure 2. The left panel shows a violet-stained histological section of a humpback ear. The right panel shows a colorized 3D reconstruction created by combining a series of histology sections like the one in the left panel.

Accomplishments: WhalEar Computational Model

In FY98, we developed the *WhalEar* software in National Instruments *LabView* and re-coded in C++. In FY99, we successfully ported the existing *WhalEar* hearing models to the DoD High Performance Computing (HPC) Hewlett-Packard Complex Exemplar and V2500assets. In FY99-FY00, we used the *WhalEar* hearing models to estimate potential sensitivity to a set of DOD sounds. This work was supported in part by a grant of HPC time from the DoD HPC Center, SPAWAR HP V2500.

An Evolutionary Programming (EP) algorithm was utilized to model the *WhalEar* filter bank since the solution space is highly multivariate and probably nonlinear. Conceptually, the inner ear of marine mammals is modeled as a series of frequency-domain bandpass filters. EP is used to optimize the number, shape and distribution of filters, effectively searching an unknown solution landscape through an algorithmic self-adaptive search. On any given iteration, variations of the model were tested for goodness of fit to a target function. The most successful

variation(s) were retained, copies were modified algorithmically, and these competing sets of model parameters were entered into the next iteration. This process was continued until the goodness of fit metric reached asymptotic levels. Success of the marine mammal hearing model was determined by its similarity in acoustic sensitivity to that of the target dolphin or whale species.

We created Evolutionary algorithms and marine mammal hearing algorithms in C++ code, demonstrated functionality on the HP Complex Exemplar/V2500, and then streamlined computational efficiency by parallelizing the highly nested, iterative Evolutionary Programming algorithm. HPC is ideally suited for Evolutionary Programming, a highly iterative cost-minimizing process that optimizes the fit of model parameters to a desired output function. By porting our models to the HPC, our intention was to "supercharge" our iterative computations through access to parallelizing capabilities. The original dolphin hearing model algorithms for this project were created in QuickBasic in the early 1990s as part of an IR project at the Naval Ocean Systems Center Hawaii laboratory. These were ported to the National Instruments LabView® programming environment in the mid 1990s. Now, we have multithreaded *WhalEar* programs distributed across multiple processors on the HP V2500. This has increased our computational efficiency dramatically, although further gains are certain. For example, one "evolutionary run" of the original code running on a fast Pentium II desktop PC took about 500 hours. Now, one run on the V2500 takes a little less than one hour. The result of this has been measurable improvement in the accuracy of our models because each model can run longer.

Three alternative bandpass filter models of the humpback whale ear were created using an evolutionary programming scheme on a V2500 high-performance computer system. Model performance was targeted toward the predicted auditory sensitivity of the humpback, the result of

our FY98-99 effort (see Figure 3 below). Predictions of humpback auditory sensitivity assumed that humpback ear structure was structurally similar to either a general mammal. Sensitivities taken from the literature were convolved with resonant frequencies estimated from a humpback whale basilar membrane structure by Ketten. The result is a predicted frequency X sensitivity "audiogram" for a humpback whale. Notice the broad range of frequencies predicted from basilar membrane structure; the actual sensitivity function also will contain components of middle ear transfer not included in this model.
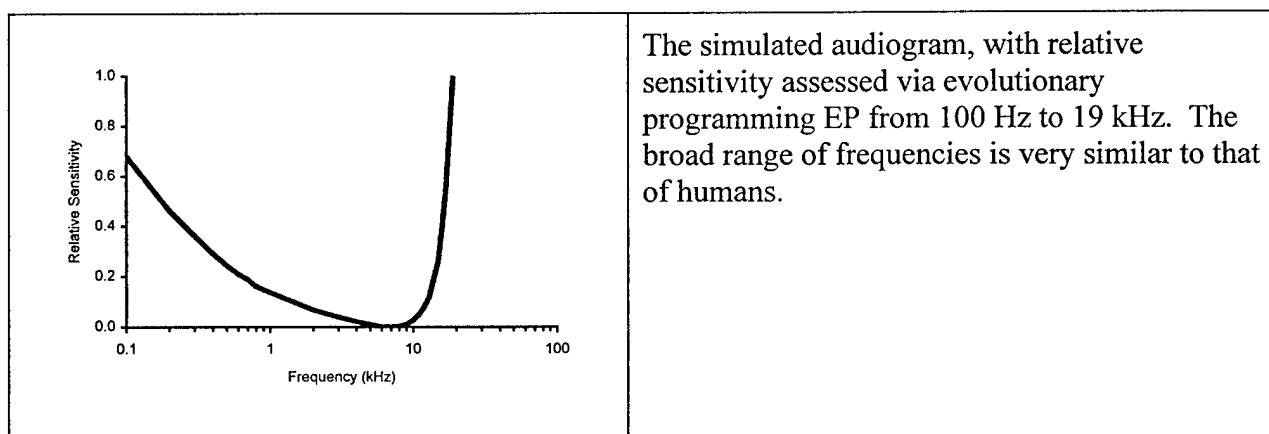

The simulated audiogram, with relative sensitivity assessed via evolutionary programming EP from 100 Hz to 19 kHz. The broad range of frequencies is very similar to that of humans.

Figure 3. Simulating a Humpback Whale Audiogram.

WhalEar filters were structured as either Gaussian-shaped or as a rounded exponential function (ROEX), a design more pertinent to neurophysiological auditory filter modeling. The primary difference between the pseudo-Gaussian and ROEX models lies in the sharpness of their peak, with ROEX having steeper skirts. The algorithms for each distribution are significantly different. To create an Evolutionary Program that could modify the shape of a pseudo-Gaussian bandpass filter, we described the filter using the following equation:

$$\text{Gain (Filter, Frequency)} = ((e^{-(x_i - (120)^{f_j/F_n})^2 / (2*(((120)^{f_j/F_n}/Q_3)/1.658)^2)}) / \sqrt{2\pi}) * S$$

The output of this function results in a symmetric bandpass filter with gain specified by the center frequency, Q, and amplitude scaling function. In contrast, the ROEX bandpass filter was described using the following equation:

$$\text{Gain (Filter, Frequency)} = A[(1 + pg)\exp(-pg)] + B[(1 + rg)\exp(-rg)]$$

Note that the low-frequency skirt (A) and high-frequency skirt (B) are independent parameters in the ROEX function. Interestingly, although the two algorithms underlying the two models differed significantly, the evolutionary programs converged to highly similar banks of best-fit filters, which are presented in Figure 4.
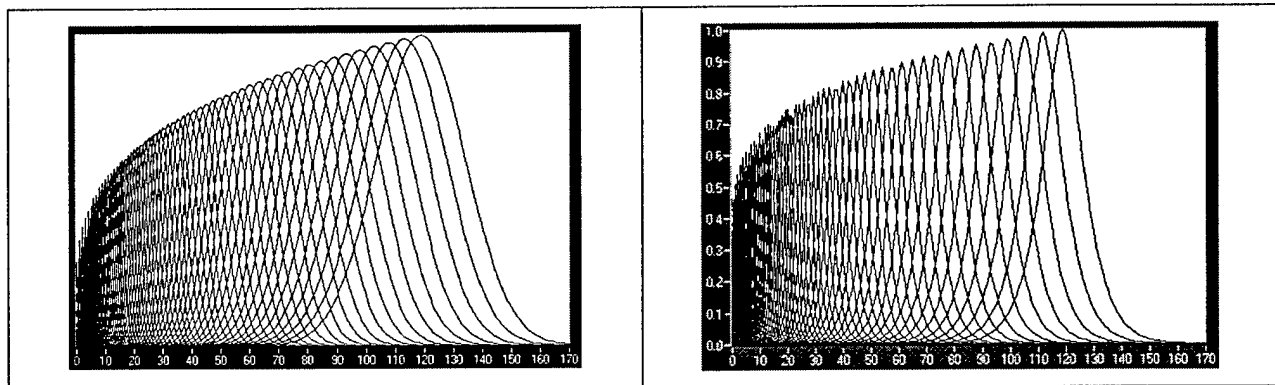

Figure 4. The Pseudo-Gaussian is on the left, and the ROEX model is in the right panel. Evolved parameters in the Pseudo-Gaussian model include Q_3, number of filters, and frequency-dependent amplitude scaling. Evolved parameters in the ROEX model include filter quality, number of filters, low-frequency tail length, and frequency-dependent amplitude scaling.

Finally, the *WhalEar* models were used to estimate humpback whale sensitivity to DOD sound types. The *WhalEar* filter banks are described by their sensitivity to sounds of different frequencies. This information was used to generate a Finite Impulse Response (FIR) filter with equivalent frequency-dependent sensitivities. The *WhalEar* computer model was converted into a functional digital filter using a Virtual Instrument created in LabView as shown in Figure 5.

The arbitrary bandpass FIR filter was implemented using 495 taps, which matched the *WhalEar*
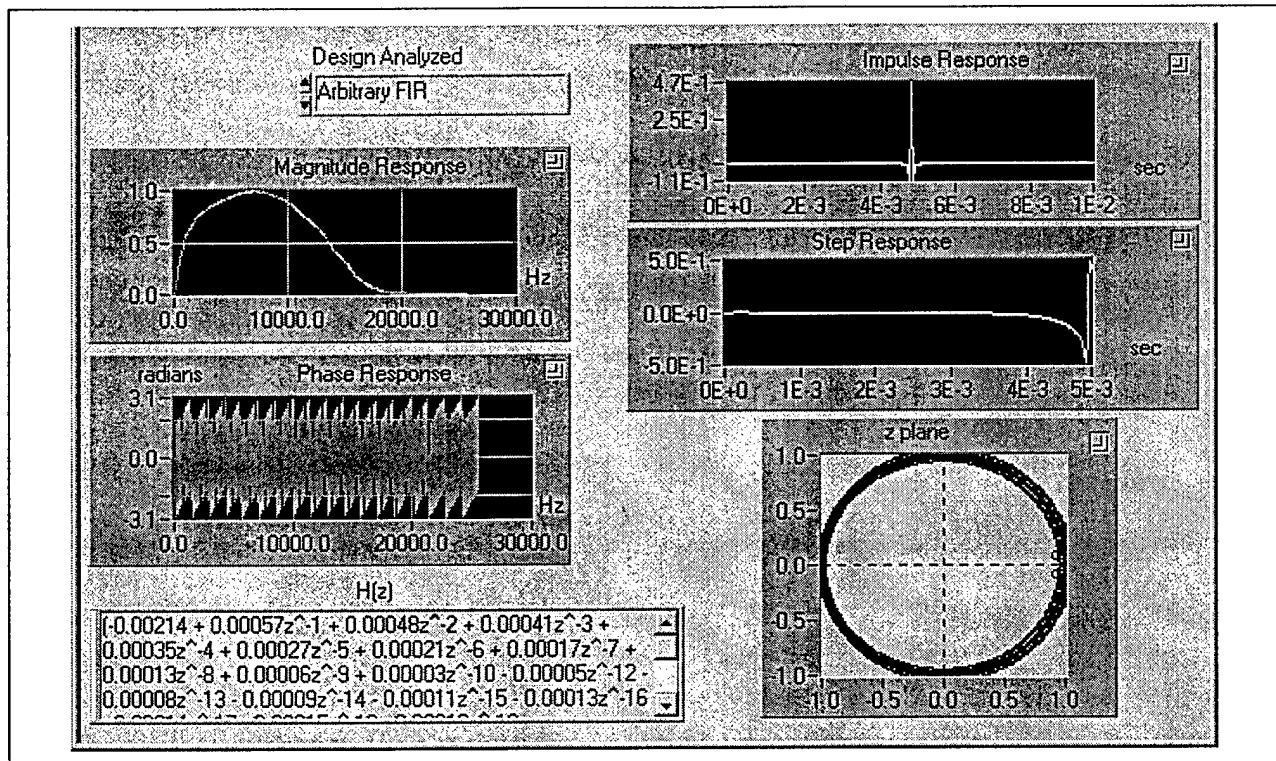
model output with 0.1 dB ripple.

Figure 5. Virtual Instrument GUI for the FIR Instantiation of the *WhalEar* Sensitivity Function. The arbitrary bandpass FIR filter was implemented using 495 taps, which matched the *WhalEar* model output with 0.1 dB ripple. The magnitude and phase response are on the left; the impulse and step response are on the right, along with a polar plot of the pole-zero placements.

The FIR instantiation of the *WhalEar* model was used to process DOD sound types from

the database compiled in this SERDP project. Sounds to which the humpback whale model is

sensitive pass through the FIR filters without substantial attenuation, analogous to good

sensitivity to those sounds. Sounds that lie outside frequencies to which the humpback whale

model is sensitivity are strongly attenuated, analogous to lack of auditory sensitivity. Two

examples are presented here. First, we passed a 5-kHz broadband sample of humpback whale

song through the FIR filter, shown in Figure 6. The frequency structure of the song was

unmodified – the humpback whale *WhalEar* model is sensitive to humpback whale sounds.

Recall the *WhalEar* was derived from humpback whale anatomical data. This is a simple proof

that the *WhalEar* FIR filter is sensible. Second, we passed a 17-Hz infrasonic blue whale B call

through the FIR filter, shown in Figure 6. As would be predicted, the blue whale call was almost

completely attenuated. Notice that the peak frequency emphasis has shifted upward from the

fundamental frequency to the higher third harmonic. Analysis of the *WhalEar* sensitivity to

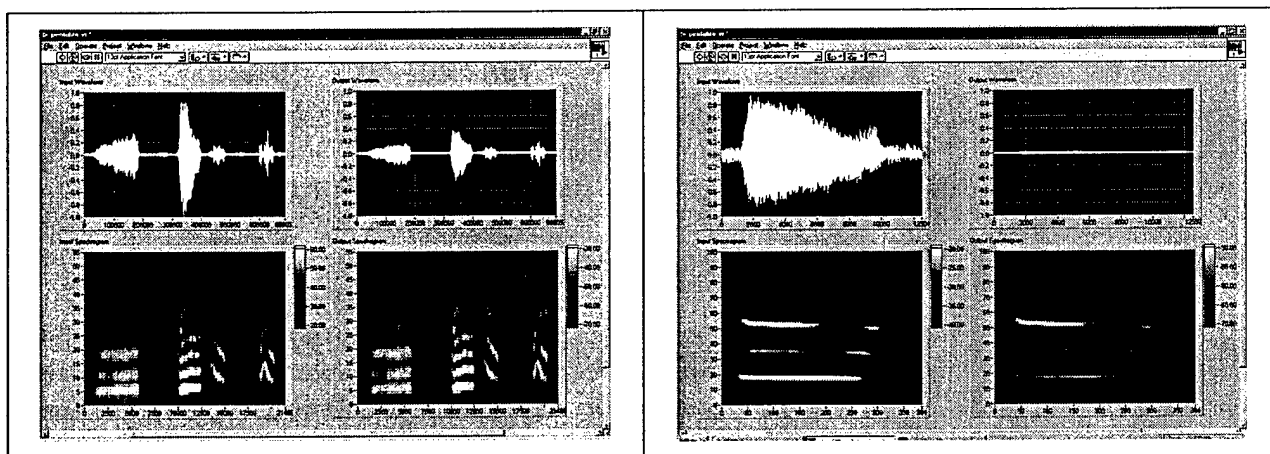DOD sound types and enhancements to the modeling process are underway.

**Figure 6. Processing whale calls with the *WhalEar* FIR filter. The left panel illustrates that
the filter is sensitive to humpback whale song. The right panel illustrates that blue whale B
calls lie outside the best sensitivity of the filter, and are thus strongly attenuated.**

In FY00, we successfully used *WhalEar* hearing models to estimate potential sensitivity

to a set of DOD sounds. Conceptually, the inner ear of marine mammals was modeled as a series

of frequency-domain bandpass filters. Evolutionary Programming was used to optimize the

number, shape and distribution of filters, effectively searching an unknown solution landscape

through an algorithmic self-adaptive search. Success of the marine mammal hearing model was determined by its similarity in acoustic sensitivity to that of the target dolphin or whale species. The broad range of frequencies predicted from basilar membrane structure is comparable to that for human hearing. These results are available in SPAWAR Technical Reports 1834 and 1835, and the computer code is available on the web (URLs provided below).

Task 2 Software/Computer Code

http://www.spawar.navy.mil/sti/publications/pubs/tr/1834/dolphinepcode.doc

http://www.spawar.navy.mil/sti/publications/pubs/tr/1835/HumpbackEPcode.doc

The digital Finite Impulse Response instantiation of the *WhalEar* model was used to process DOD sound types from the database compiled in this SERDP project. Sounds to which the humpback whale model is sensitive pass through the FIR filters without substantial attenuation, analogous to good sensitivity to those sounds. Sounds that lie outside frequencies to which the humpback whale model is sensitivity are strongly attenuated, analogous to lack of auditory sensitivity. The modeling of sound exposure with Navy sound types is continuing, using midrange tactical sonar waveforms described in Table 1.

Mode	Waveform	53C	ASFS HULL	ASFS MFTA
SD	CW30	YES	NO	NO
	CW100	YES	NO	NO
	CW300 *	YES	YES	TBD
	CP30/200	YES	YES	NO
	CP100/200 *	YES	YES	TBD
	CP300/200 *	YES	YES	TBD
	CP300/1000	NO	YES	TBD
	TRRDT	YES	NO	NO
SD SOA	SOA CP10/800	NO	YES	NO
	SOA CP30/800	NO	YES	NO
	SOA CP100/800	NO	YES	NO
	SOA CP30/1800	NO	YES	NO
VD	CP500/100 - CW500 *	YES	NO	NO
	CP500/100 - CW1000 *	YES	NO	NO
	CP1000/400 - CW1000 *	YES	NO	NO
	CP500/100 - CWS1000	NO	YES	YES
	CP1000/400 - CWS1000	NO	YES	YES
	CP2000/400 - CWS2000	NO	YES	YES
	CP2000/100 - CWS2000	NO	YES	YES
VD SOA	SOA CP10/800	YES	NO	NO
	SOA CP30/800	YES	NO	NO
	SOA CP100/800	YES	NO	NO
VD	FSK 3x100 NOL	YES	NO	NO
	FSK 10x100 NOL	YES	NO	NO
	FSK 10x200 NOL	YES	NO	NO
	FSK 5x100 OL	YES	NO	NO
	FSK 10x200 OL	YES	NO	NO
	FSK 20x100 OL	YES	NO	NO
	FSK 20x200 OL	YES	NO	NO
	RRDT	YES	NO	NO

Mode	Waveform	53C	ASFS HULL	ASFS MFTA
TK1,TWS,TOS	CW10	YES	NO	NO
	CW30	YES	NO	NO
	CW100	YES	NO	NO
	CW300	YES	NO	NO
	CWS300	NO	YES	NO
	CP30/200	YES	YES	NO
	CP100/200	YES	YES	NO
	CP300/200	YES	YES	NO
	CP300/1000	NO	YES	NO
	CP500/100 - CW500	YES	NO	NO
	CP500/100 - CW1000	YES	NO	NO
	CP1000/400 - CW1000	YES	NO	NO
	CP500/100 - CWS1000	NO	YES	NO
	CP1000/400 - CWS1000	NO	YES	NO
	CP2000/400 - CWS2000	NO	YES	NO
	CP2000/100 - CWS2000	NO	YES	NO
	FSK 3x100 NOL	YES	NO	NO
TK1,TWS,TOS	FSK 10x100 NOL	YES	NO	NO
	FSK 10x200 NOL	YES	NO	NO
	FSK 10x300 NOL	YES	NO	NO
	FSK 30x300 NOL	YES	NO	NO
	FSK 5x100 OL	YES	NO	NO
	FSK 10x200 OL	YES	NO	NO
	FSK 20x100 OL	YES	NO	NO
	FSK 20x200 OL	YES	NO	NO
TK1	FSK 60x200 OL	YES	NO	NO
	CP2000/800 - CW1000	YES	NO	NO
	CP2000/800 - CWS2000	NO	YES	NO

* AAP/ETC Training Waveforms
CP is presented as Pulse length (ms)/Bandwidth (Hz)

Table 1. Unclassified summary of tactical sonar waveform parameters.

Task 2 Technology Transfer.

The actual auditory sensitivity function of the whale also will be shaped by components of middle ear transfer that were not scheduled in the current model. We recommend advanced development of *WhalEar* models that includes biomechanical engineering models of the middle ear complex. Anatomical data and validated engineering models exist, which reduces risk to advanced development. The largest data gap is the lack of direct measures of baleen whale hearing on which the *WhaleEar* models would be validated, and the technology required to make those measurements.

Task 2 Publications.

Houser, D. S., Helweg, D. A., Chellapilla, K., and Moore, P. W. B. (In Press). Optimizing Models of Dolphin Auditory Sensitivity Using Evolutionary Computation. *Bioacoustics,* Vol. 12.1.

Helweg, D. A., Houser, D. S., and Moore, P. W. (2000). Creation of dolphin-like spectrum filters through the use of evolutionary programming. *SSC San Diego Technical Report 1834.*

Helweg, D. A., Houser, D. S., and Moore, P. W. B. (2000). An integrated approach to the creation of a humpback whale hearing model. *SSC San Diego Technical Report 1835.*

Helweg, D.A., Houser, D.S. & Moore, P.W.B. (1999). Computational Models of Marine Mammal Hearing. *FY99 Annual Report to the Department of Defense High Performance Computing Program.*

Helweg, D.A., Houser, D.S. & Moore, P.W.B. (2000). Computational Models of Marine Mammal Hearing. *FY00 Annual Report to the Department of Defense High Performance Computing Program.*

Houser, D. S., Helweg, D. A., and Moore, P. W. B. (2001). A bandpass filter-bank model of auditory sensitivity in the humpback whale (*Megaptera novaeangliae*). *Aquatic Mammals, 27.2,* 82-91 .

Houser, D. S., Helweg, D. A., and Moore, P. W. B. (2000). Optimization of a dolphin hearing model to relative sensitivity and frequency discrimination through simple aggregate selection. *Proceedings of the 2000 Congress on Evolutionary Computation, 2,* 844 - 850 (Washington DC: IEEE Press).

Houser, D. S., Helweg, D. A., Chellapilla, K., and Moore, P. W. (1999). Creation of a biomimetic model of dolphin hearing through the use of evolutionary computation. *Proceedings of the 1999 Congress on Evolutionary Computation, 1,* 496 – 502 (Washington DC: IEEE Press).

Task 2 Abstracts/Presentations

Helweg, D.A. (1999). A computational model of humpback whale hearing. Invited presentation to the International Bio-Acoustical Council. April 1999.

Houser, D. S., Helweg, D. A., and Moore, P. W. B. (2000). Optimization of a dolphin hearing model to relative sensitivity and frequency discrimination through simple aggregate selection. *The Congress on Evolutionary Computation.*

Houser, D. S., Helweg, D. A., Chellapilla, K., and Moore, P. W. (1999). Creation of a biomimetic model of dolphin hearing through the use of evolutionary computation. *The Congress on Evolutionary Computation.*

Houser, D. S., Helweg, D. A., and Moore, P. W. B. (1999). Modeling cetacean ear filters by means of evolutionary computation. 138th Meeting of the Acoustical Society of America, November 1999. *J. Acoust. Soc. Am.,* **106**(4.2), 2281.

Task 2 Lessons Learned.

The computational models of baleen whale hearing and auditory processes are founded upon comparative mammalian sensory processes and incorporate information about marine mammal psychophysics and neuroanatomy. At the core of the modeling effort, Woods Hole Oceanographic Institution was scheduled to provide state-of-art predictions of hearing ranges for several species of baleen whales, based upon comparative anatomical analyses (humpback, fin,

blue and gray whales). One ear was measured and modeled (see Task 2 Accomplishments above). Although the timeframe and funding has been sufficient for preparation, measurement, and analysis of most of the baleen whale ear samples that had been scheduled for this study, Woods Hole Oceanographic Institution does not appear to be able to deliver the scheduled analyses and reports. This not only impacts the anatomical understanding of baleen whale hearing, but also has prevented scheduled progress and Technology Transfer on the computational *WhalEar* models. We have not been able to proceed with (1) the modeling of masking effects and (2) integration of *WhalEar* models and the *SWAM* toolkit.

Task 3. Smart Whale Acoustic Monitor (SWAM)

Accomplishments

The objective of Task 3 was to develop an automated system to detect and identify blue and fin whale calls, and log the occurrence using the decommissioned San Nicholas Island SOSUS arrays. Included was a thrust to automate the process of determining the position of the calling whale using the directional listening capabilities afforded by arrays of hydrophones. The automated Smart Whale Acoustic Monitor (*SWAM*) system was developed in a modular fashion, keeping all modules compatible with SOSUS-type signal processing parameters. The *SWAM* tool was used to construct histories of whale vocalization behavior off Southern California. These histories have been combined with position information to yield maps of whale occurrences as a function of location across the year. Peaks in calling behavior are indicative of "hotspots" that could be a factor in at-sea environmental compliance issues.

The *SWAM* modules were developed using a suite of C-based software including National Instruments LabView®, LabWindows®, and Borland C. Risk was reduced using Commercial Off The Shelf digital signal processing hardware. Because SOSUS data are

classified, all module development has required development of unclassified simulation tools

that allowed software to be debugged and benchmarked prior to processing of classified data.

Results presented in this report are confined to output from unclassified simulation tools.

Development of the *SWAM* toolkit focused on selection of a sensible signal processing

architecture, but not on code optimization for real-time operation. The *SWAM* modules operate

off-line, although call detection and logging can be done in real time. Figure 7 shows the

Graphic User Interface for the signal acquisition, call detection, and logging. Raw array data are

anti-alias filtered, amplified, multiplexed, and digitized at 2048 samples per second per channel.

The raw array data are written to disk. Pilot sampling schemes utilized different combinations of

duty cycle and hours of sampling. Currently, the arrays are sampled for 20 minutes every hour

for 22 hours most days of the week. The program suspends data sampling every night to perform

offline data management and archiving. This sampling scheme is sufficient to detect most

calling whales, and over the course of many months of continuous sampling generated a
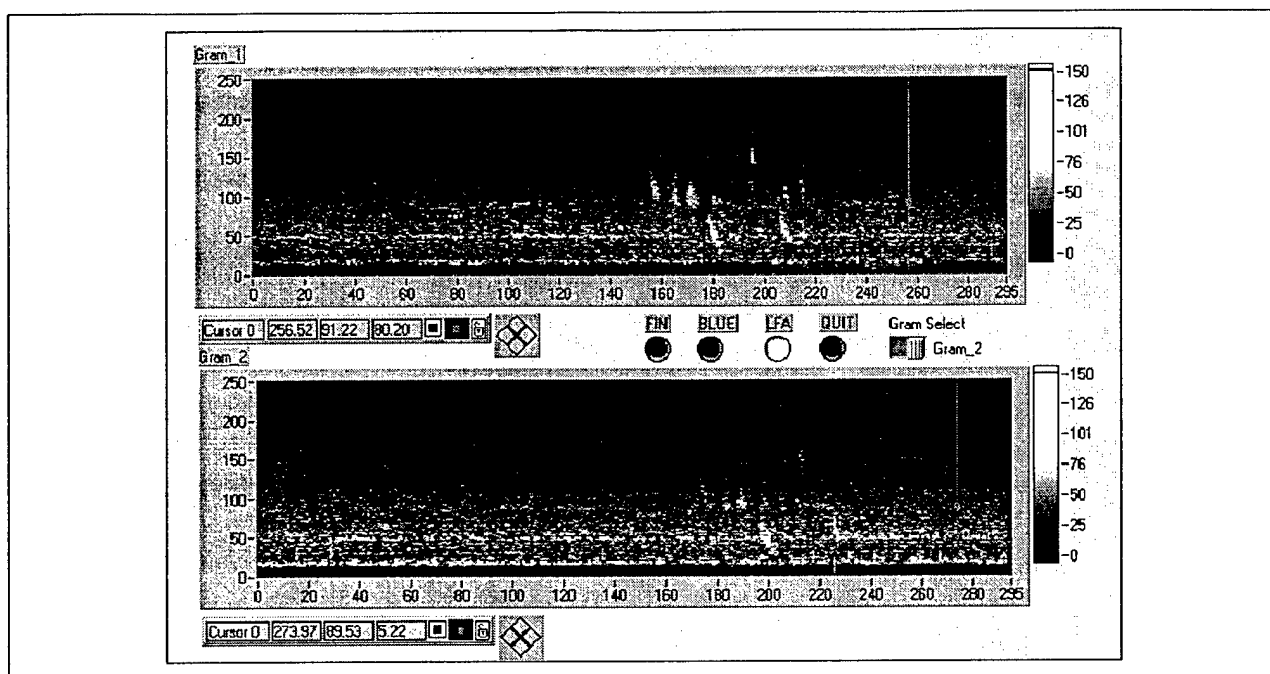
significant database.

Figure 7. SWAM Real-Time Detect-and-Log Screen. This panel illustrates the user interface at the array site on San Nicholas Island. This module was developed in FY99. The user can select a channel from each array, which the automated SWAM system monitors for whale calls. The downswept waveforms displayed here are the same whale calls arriving at each sensor.

In *SWAM*, whale calls are detected using narrow-band energy detection after passing the raw data through a three-pass peak shearing whitening filter. The whitening filter can function as a constant false alarm rate filter (CFAR) if the whitening threshold adapts to local ambient noise levels. CFAR is not implemented at present. The whitening filter constructs an estimate of the noise spectrum and then removes this from incoming samples. The spectral noise in a bin $r1_n$ is estimated by replacing potential signal spikes with a power average M_l from the bins on either side of the signal bin using the following algorithm:

$$\text{Spectral Noise Estimate(bin) } r1_n = \begin{cases} x_n & \text{if } x_n \leq k_1 M_1 \\ M_1 & \text{if } x_n > k_1 M_1 \end{cases}, \text{where } M_1 = \frac{1}{W}\sum_{n \in \Omega} x_n$$

This is repeated twice, and then the real spectrum is divided by the noise estimate in the third pass. This has the effect of increasing the signal to noise ratio of whale calls by removing ambient noise, which thus makes them more detectable.
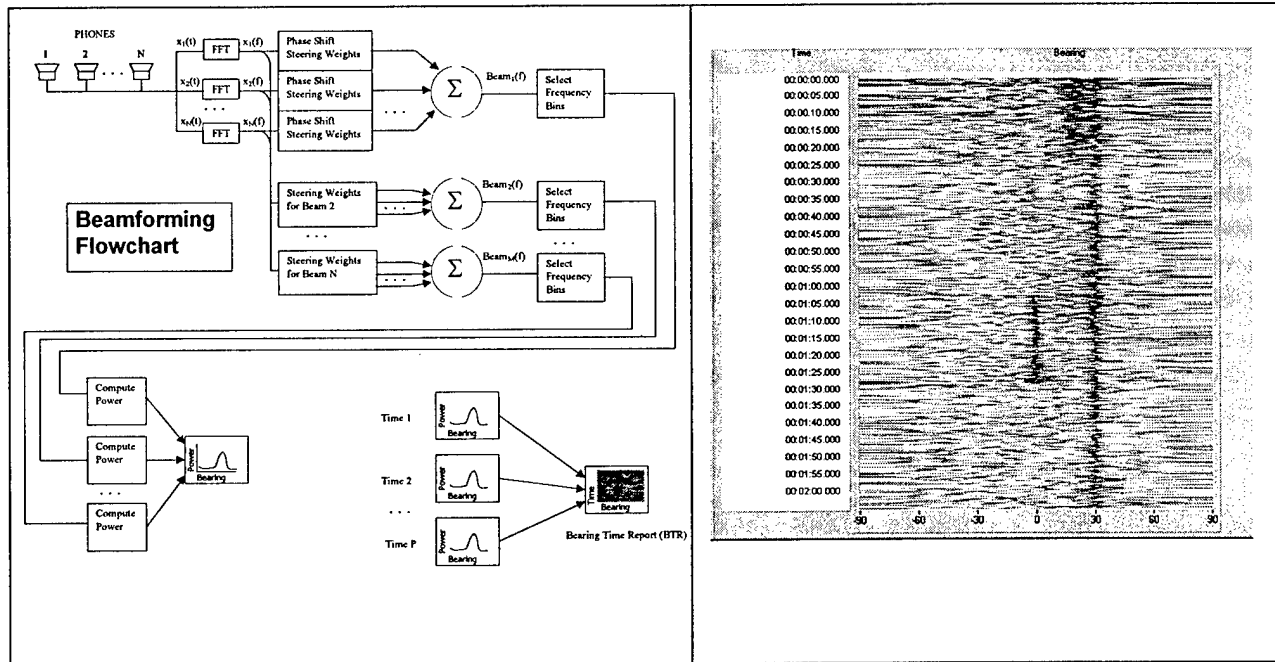

Figure 8. Beamforming Flowchart. An adaptive frequency-domain beamformer was created in FY99. Output from this module is used to generate a Bearing-Time Report, which shows bearing changes of a sound source over time. Three sound sources appear as black lines across the gray background.

One major thrust in FY99/00 was the development and groundtruthing of an adaptive frequency domain beamforming (ABF) module. The output of the ABF is displayed in a Bearing Time Report (BTR), which allows the user to select and track sound sources. The flowchart is shown in Figure 8. Beamforming, or directional listening, increases precision in mapping the relationship between whale calls and actual whale occurrences. Beamforming increases signal to noise ratio by attenuating sounds coming from outside the listening direction. Importantly, without beamforming we can record the time at which a whale call occurred but not the location

of the calling whale. If more than one whale is vocalizing at the same loudness, we have no

ability to discriminate among them. With beamforming, we can record the time and location

from which a whale calls, increasing precision by permitting spatial separation of multiple

calling whales. The whale tracks become visible using this method, presented in the right panel

of Figure 8.

Currently, we are managing the display of whale locations using a GIS display, presented

in Figure 9. The upper left panel provides a standard bioacoustic-type spectrogram display.

Detected calls are automatically beamformed, displayed (U) in as a BTR the lower left. Best

beam is estimated from the BTR and plotted as a radial on the SOCAL GIS display on the right.
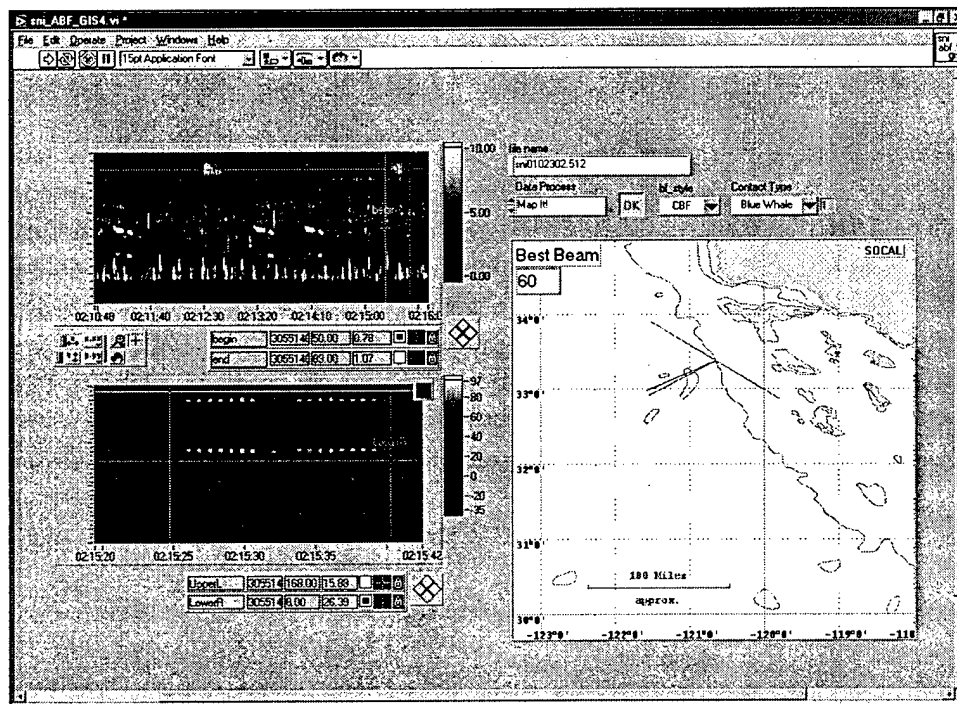
Figure 9. SWAM Graphic User Interface. Display panels include spectrogram output, BTR, and GIS display of bearings. All are designed for unclassified viewing.

Several data transfer methods were evaluated in FY99, including SIPRnet transmission of classified data and modem transmission of unclassified derived data. The goal of this evaluation was to determine whether data archival at the remote San Nicholas Island site could be replaced with more efficient data transfer to the analysis site at SPAWARSYSCEN in San Diego. To retain a robust dataset, it was ideal to transmit raw array data, but these are classified and require large bandwidth. T1 transmission was tested in FY98 and was found to be unsatisfactory for logistical reasons. N774 granted permission was granted for SIPRnet transfer of raw array data, and modem transfer of unclassified derived data late in FY99. Configuring the computer system to meet security requirements for SIPRnet transmission proved to be too costly, given the project budget. Currently, unclassified data continue to be transmitted over secure modem.

As described above, the arrays have been sampled for 20 minutes every hour for 22 hours most days of the week since July 1999. This sampling scheme is sufficient to detect most calling whales, and over the course of the past two years has generated a large database of array timeseries. Seasonal patterns of southern California residency of fin and blue whales is revealed in Figure 10. As predicted by NOAA Fisheries visual survey data, the peak of fin and blue whale residency around the Channel Islands occurred in autumn. Whales tended to aggregate around steep bathymetric features to the northwest and northeast. Correcting for survey effort reduced smearing, illustrated in the bottom panels of Figure 10. Note the substantially lower abundance of both fin and blue whales in the autumn of 1999 as compared to the higher abundance in autumn 2000, an occurrence perhaps related to the end of the La Niña event.
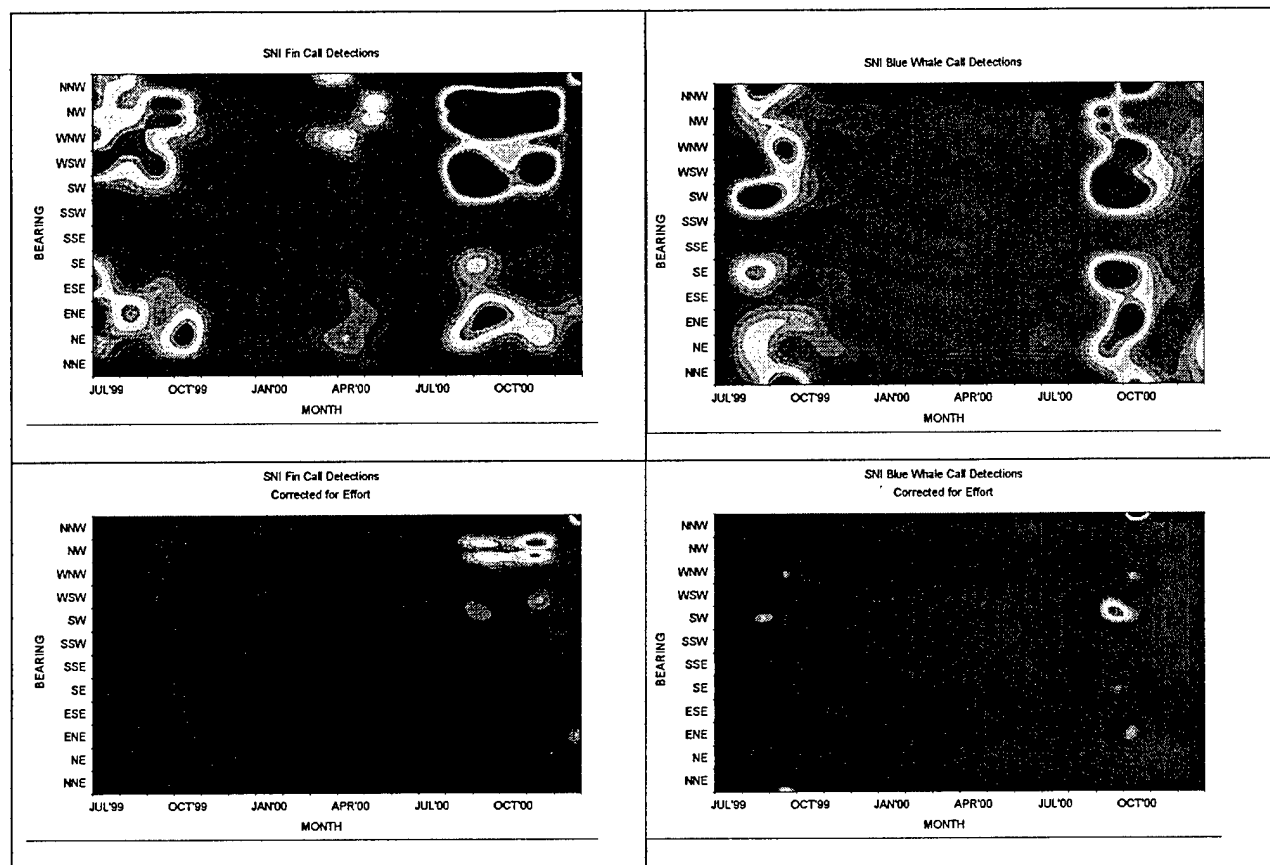
Figure 10. Seasonal changes in residency of fin and blue whales in SOCAL water derived using the *SWAM* toolkit. Time runs on the horizontal axis spanning July 1999 – December 2000. Bearing runs from N to E to S to W to N from the bottom up on the vertical axis. TOP: Total fin whale call detections on the left, and blue whale call detections on the right. BOTTOM: Call detections corrected for effort (calls per hour of observation); fin whales on the left, and blue whales on the right.

Task 3 Technology Transfer

The SWAM technology developed in Task 3 has been transferred to the Office of Naval

Research "Marine Mammal Monitoring" program. Development of the *SWAM* toolkit has

focused on selection of a sensible signal processing architecture, but not on code optimization for

real-time operation. This will occur as part of the advanced development, along with

modification to adapt the automation processes to new species of concern and array

configurations.

Task 3 Papers/Manuscripts/Reports

Helweg, D.A, Sheldon, J. and Cummings, W. (Submitted). Comparison of historical and
contemporary contributions of mysticete vocalization to ambient noise in southern
California waters. *U.S. Navy Journal of Underwater Acoustics.*

Helweg, D.A. and Teeter, W.L. (In review). A white noise-constrained adaptive beamformer for
processing whale vocalizations.

Helweg, D.A. and Teeter, W.L. (In review). Automating acoustical methods for identification
and tracking of vocalizing whales.

Helweg, D.A. (1998). Automating the acoustic monitoring of New Zealand waters for migrating
humpback whales (*Megaptera novaeangliae*). *SSC San Diego Technical Report 1765.*

Teeter, W.L. (1999). A cost/benefit comparison of using the San Nicholas Island SOSUS assets
for marine mammal applications. White paper report to SERDP Project CS-1082.

Abstracts/Presentations

Helweg, D.A. (1999). Automated detection and species identification of blue and fin whale
calls. Invited presentation to the International Bio-Acoustical Council. April 1999.

Helweg, D.A. (1999). Detection and species identification of baleen whale calls. Invited
presentation to the 138th Meeting of the Acoustical Society of America, November 1999.
J. Acoust. Soc. Am., **106**(4.2), 2162.

Helweg, D.A. (1999). Experiences with San Nicholas Island Arrays. Invited presentation at the
SOSUS Dual-Uses Wrap up Workshop. Federation of American Societies of
Experimental Biologists. September 1999.

Helweg, D.A. (2000). Automating the identification and tracking of cetaceans by acoustical
methods. Invited tutorial, Odense University Advanced Bioacoustics Course. Odense,
Denmark.

Helweg, D.A. (2000). Seasonal contribution of mysticete vocalization to ambient noise in
southern California waters. Invited presentation to the 140th Meeting of the Acoustical
Society of America, December 2000. *J. Acoust. Soc. Am.*, **108**(5.2), 2613.

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